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Climate vs. anthropogenic changes in North Adriatic shelf sediments influenced by freshwater runoff

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ABSTRACT: Land–ocean coupling was investigated for the Adige River-Adriatic Shelf system by analyzing precipitation, water discharge and suspended load records over the period 1922–2000 and by comparing them with the $^{210}Pb_{ex}$ and porosity depth profiles of 4 marine cores taken along the riverborne sediment transport pathway on the shelf. The results show that precipitation was affected only by minor variations in yearly and seasonal amounts but was accompanied by a significant decrease (increase) in the number of wet days (precipitation intensity). River discharge—which is strongly influenced by total precipitation as well as by the number of wet days (in contrast to the quantitatively less important precipitation intensity)—shows a continuous decrease throughout the whole period. A significant decrease in suspended load is recorded after the 1940s, and meteorological and hydrological data suggest a major discontinuity over the same period, which was also recorded by marine sediments as a significant decrease in accumulation rates of fine materials. After the 1970s a further change in water discharge is observed in the river-system lowlands, recorded on the Adriatic shelf as intermittent sediment accumulation, and probably related to major floods. Changes seem to be mostly anthropogenic, such as progressive withdrawal of water and sediment for agricultural and civil uses, as well as damming for irrigation purposes and for generation of electricity.

KEY WORDS: Precipitation · River hydrology · Land–sea interactions · Sediment records · Adige River · Adriatic Sea · Italy

1. INTRODUCTION

Over the last century, important climatic changes have occurred through a combination of natural variability and anthropogenic forcing. It is, therefore, very important to understand causes and mechanisms of climate change, and their impact on the environment. Research uses both historical datasets and information stored in natural archives such as glaciers, trees and sediments. In this way, it is possible to shed light on climate fluctuations, trends, mechanisms and causes over a wide range of time scales (Houghton et al. 2001). It is also very important to understand whether a given change in climate results in changes in weather extremes, or rather in a change in weather trends (Benestad 2003a,b, Hanson et al. 2006).

Climate change can have marked impacts on inland hydrological regimes (Inman & Jenkins 1999, Syvitski & Morehead 1999, Hu et al. 2001), thus influencing key processes in coastal areas where rivers supply large quantities of suspended matter together with dissolved chemicals from natural and anthropogenic sources. As a consequence prodelta areas, due to the high accumulation rates of fine materials, can be useful to reconstruct the history of river supplies and accumulation patterns. In fact, there is a direct relationship between type and amount of fluvial inputs and frequency and intensity of precipitation on the mainland (Alvisi et al.

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2000). However, it has become increasingly difficult to assess the impact of changes in the sediment flux to the coastal zone because of conflicting anthropogenic impacts (Syvitski 2003). This is particularly true for the Mediterranean region, where there is a long history of anthropogenic settlement and activity along all its coasts.

In the framework of climatic and environmental research, North Italy and the West Adriatic shelf provide a unique opportunity to compare historical data series of the main meteo-climatic parameters, such as precipitation and temperature, with marine sedimentary records. The North Adriatic Sea is surrounded by the high relief topography of the Alpine, Apennine and Dynaric mountain systems, which tend to amplify meteorological disturbances and are the source of a great amount of sediments. As a consequence, the Adriatic coastal area is strongly influenced by river-borne particulate materials that are distributed over the shelf by marine circulation. The Adriatic system associated with the Adige River was therefore chosen to study conceptual aspects of the land–ocean interaction.

In this context, we analysed precipitation and river discharge variability and trends over the 20th century and determined how these signals are recorded in marine sediment; in addition we have analysed information related to the impact of climate vs. human activities. These issues are particularly important for the development of coupled land–ocean models that provide a basis for predicting hydrological, geo-morphological and ecological evolution under different environmental scenarios in the near future (Summerfield & Hulton 1994, Wasson 1996, Syvitski & Morehead 1999, Ravaioli et al. 2003, Vichi et al. 2003).

2. STUDY AREA

The Adige River basin encompasses an area of about 12 100 km^2 in NE Italy (Fig. 1). From its headwaters at 1550 m a.s.l., it flows south through the eastern Alps for nearly 250 km and then SE in the Veneto alluvial plain for the rest of its 409 km course, before reaching the Adriatic Sea just North of the Po River delta (Fig. 1). It has the third largest basin in Italy after the Po and Tiber rivers, is the second longest river in Italy and drains intensely cultivated and industrialized areas (Di Silvio 1975).

The river basin covers 2 different climatic regions. The mountain sector has an Alpine climate, whereas the lowlands are influenced by the climate of the

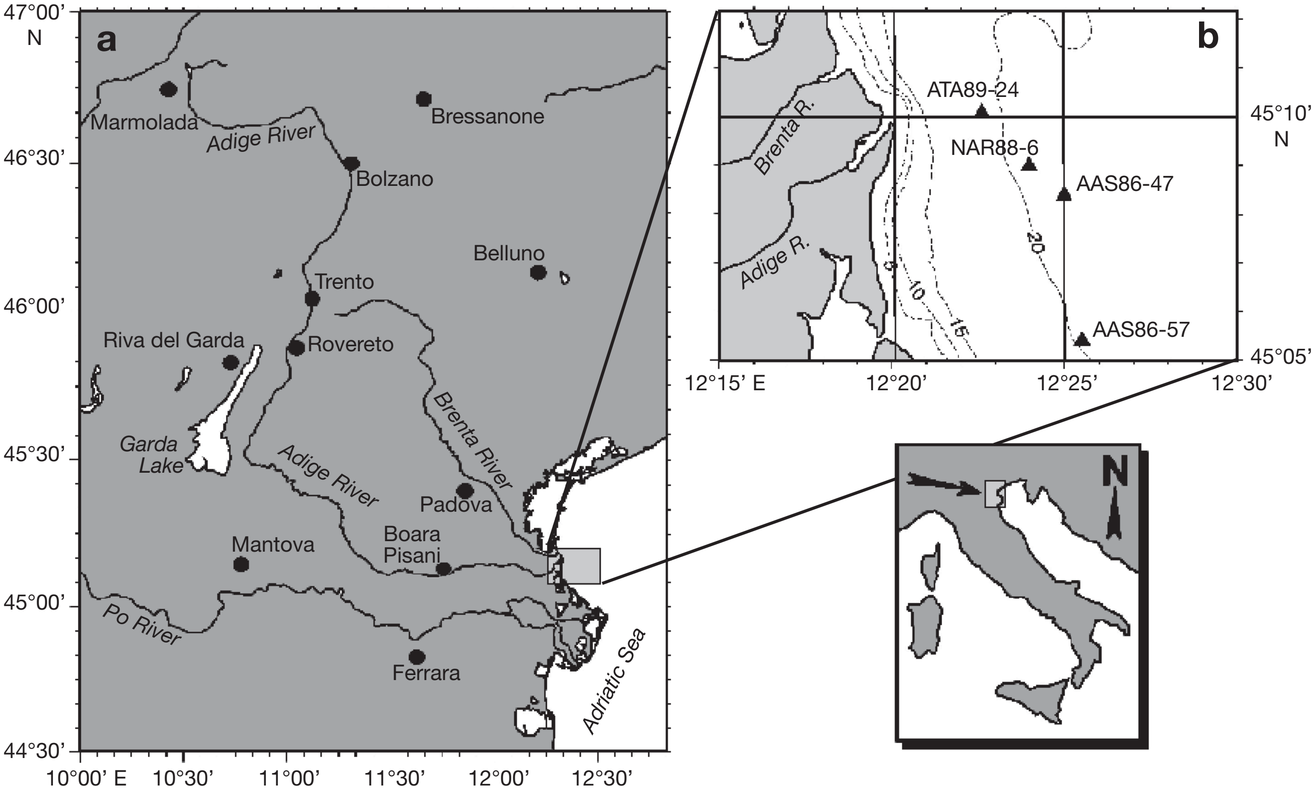

Fig. 1. (a) Drainage basin of the Adige River; (●) pluviometric and hydrological stations. (b) Marine study area; (▲) core samples; dashed lines: isobaths (m)

eastern Po Plain. The 2 regions have completely different pluviometric regimes: in the Alps the wettest season is summer, whereas the winter is very dry. In the eastern Po Plain the precipitation displays maxima in spring and autumn and minima in summer and winter. Yearly average precipitation of the Adige River basin lowlands displays a very smooth spatial pattern with values between 700 and 1000 mm, whereas for the Alpine sector there are very strong spatial gradients and a higher range of values (500 to 2000 mm; Mennella 1967).

The Adriatic Sea is the most extensive shallow continental shelf of the Mediterranean Sea (800 km from NW to SE) and is an important source of nutrient-rich and dense water masses flowing into the East Mediterranean basin (Gačič et al. 1999). The general thermohaline circulation of the whole basin is dominated by cyclonic sub-gyres interconnected by coastal currents, resulting in transport and deposition of sediment predominantly along the Italian coast (Franco et al. 1982, Malanotte-Rizzoli & Bergamasco 1983, Orlich et al. 1992, Artegiani et al. 1997a,b). Fine materials accumulate along the coast in belts that are hydraulically sorted by grain size (Franco 1970, Dal Cin 1983), in accordance with the classical model of modern sedimentation on continental shelves, i.e. coastal sands and mud, with shelf relict sand further offshore (Frignani et al. 2005). There are also transition areas between the main lithological types.

The sedimentation pattern matches the hydrodynamic circulation and consists of a belt of recent Holocene muddy sediments interposed between coastal and offshore relict sands (Trincardi et al. 1996). The sedimentary evolution of the Adriatic shelf is, in fact, strongly influenced by riverine particulate materials as well as by seasonal changes of meteo-marine oceanographic conditions, and sediment accumulation results from the dynamic equilibrium of these main elements (e.g. Alvisi et al. 2001). In winter, the currents are essentially cyclonic and force the Italian river plumes southward, along the western coast of the basin. The water column is more or less homogeneous and is separated from more saline waters to the east (Artegiani et al. 1997a,b). Wave motion and tidal currents keep the coastal zone free from stratification to a depth of 10 to 12 m. Under these conditions shelf sediments are exposed to wind and wave action, and this may result in considerable resuspension and erosion (Price et al. 1993, Matteucci & Frascari 1997). The wave energy on the bottom down to the 15 m isobath likely promotes resuspension with the potential for removal of fine material (Fox et al. 2004).

The morphology of the Adige river mouth is continuously changing due to the variations of both water and particle loads and hydrodynamics of the coastal zone (Zunica 1971, Dal Cin 1983). Part of the sand transported to the sea is deposited at the mouth, the remainder being distributed by local currents alongshore in a prevailing northward direction. Suspended matter is dispersed in the same direction and only at ~2 km offshore is it diverted toward the SSE, thanks to the influence of the counter-clockwise current of the North Adriatic Sea. Local alongshore currents, which are mainly wave-induced and take place essentially in the breaker zone, act at different time, space and energy levels from the thermohaline general circulation. Thus, the 2 corresponding sediment transports are not directly interconnected.

The shelf study area is influenced by the sedimentation of fine particles coming from both the Adige and Brenta rivers, but we discuss only the former because the 2 hydrological patterns are similar, and the Adige flow is 3 times higher than that of the Brenta (see Fig. 2). Minor differences between the runoff patterns of the 2 rivers are most likely related to the relative contribution of snow to the total precipitation; this influences the Adige basin to a greater degree because of more extensive — and higher altitude — mountain territory which retains snow later in spring and earlier in autumn.

3. DATA AND METHODS

3.1. Meteorology

Daily precipitation records of the 1922–2000 period were obtained for 10 stations, 7 of them belonging to the Italian Hydrographical Service Network and 3 to astronomical observatories (Fig. 1). The records were homogenised on a daily basis and missing data were obtained using statistical procedures described in Brunetti et al. (2004). For each station, we calculated the total precipitation (TP), the number of wet days (WD), and the mean amount of precipitation per wet day (precipitation intensity, PI). Regional average series were then obtained by averaging the monthly TP, WD and PI series over all the stations.

3.2. Hydrology

Monthly series of maximum and mean river discharges (Qmax and Qmean, respectively) were recovered for the period 1922–2000 for the hydrological stations of Adige Trento (AT) and Adige Boara Pisani (ABP), whereas suspended load data are available only for the periods 1929–1942 and 1958–1972 at ABP, as mean turbid discharge (Qt). The dataset drew from the Hydrological Annals of both the Hydrographic Service of Venice of the Ministry of Public Works and the Provincia Autonoma di Trento-Servizio Utilizzazione delle Acque Pubbliche-Ufficio Pianificazione e Rilevazioni Idriche. The series were checked for homogeneity with statistical methods (Craddock 1979) and metadata.

TP, WD, PI, Qmax and Qmean seasonal and annual series were constructed from monthly series. In line with meteorological convention, yearly values were made to correspond to the period from 1 December to 30 November, and dated by the year in which January is included. Winter, spring, summer and autumn values refer to the December–February, March–May, June–August, and September–November intervals, respectively.

Seasonal and annual regional precipitation and river discharge anomaly series were analysed for trends by means of the Mann-Kendall non-parametric test (Sneyers 1990). The slopes of the trends were calculated by least square linear fitting.

3.3. Core sampling and sedimentological analyses

The marine study area (Fig. 1b) includes the Adige and Brenta River estuaries and the prodelta area down to 25 m water depth. The 4 sediment cores (collected with a gravity corer between 1986 and 1989 on cruises AAS-86, NAR-88 and ATA-89) were selected firstly because of their relatively uniform sedimentary record, since our study required data from a period with stable sedimentary conditions, and secondly because they represent a time interval similar to the available instrumental data records. After collection, sediments were refrigerated at 4°C. In the lab, the cores were scanned for the whole-core magnetic susceptibility and then opened, photographed, described and sectioned in intervals of 1 to 4 cm, with higher resolution close to the core top. Porosity and bulk dry density were obtained from the percent water content (Berner 1971) assuming a dry sediment density of 2.55 g cm^{-3}. Grain size analyses were carried out by wet sieving at 63 μm to separate sand, and then by a Sedigraph model 5100 ET (Micromeritics) to evaluate the distribution pattern of the muddy fraction (silt and clay). The organic fraction was eliminated by a pre-treatment with H_2O_2.

Whole-core magnetic susceptibility depth profiles were obtained by scanning the cores with a MS2 meter (Bartington) and a loop sensor (80 mm diameter) in order to allow lateral core and derived data correlations, as suggested by Oldfield (1991) and Verosub & Roberts (1995). The other analyses were performed on samples dried at 60°C and disaggregated.

3.4. Radiometric analyses

Core dating was based on ^{137}Cs and ^{210}Pb activity-depth profiles. ^{137}Cs was measured by non-destructive gamma spectrometry (Frignani & Langone 1991). ^{210}Pb activity was determined by alpha spectrometry of the granddaughter nuclide ^{210}Po, after acid extraction and spontaneous plating on silver planchets (Frignani & Langone 1991). Excess ^{210}Pb ($^{210}Pb_{ex}$) activity was determined by subtracting from the total the value of supported activity determined from the nearly uniform values at the base of the cores. These background values were 17.8, 18.1, 19.2 and 18.5 Bq kg^{-1} in cores ATA89-24, NAR88-6, AAS86-47 and AAS86-57, respectively. All concentrations are based on dry weights.

3.5. Core dating

The pattern of ln($^{210}Pb_{ex}$), values vs. depth in our cores are nearly linear, thus allowing the calculation of sediment accumulation and mass accumulation rates by means of a simple model (Robbins 1978, Sorgente et al. 1999). However, since no simple model can account for the accumulation of both sediment particles and $^{210}Pb_{ex}$ in this type of coastal environment (Frignani & Langone 1991, Alvisi et al. 2001), we calculated rates and dates using the following assumptions: (1) constant flux of $^{210}Pb_{ex}$ and constant sedimentation (CF-CS); (2) constant initial concentration (CIC) applied to both the upper and lower part of the profiles, separated by a significant discontinuity; and (3) constant rate of supply of $^{210}Pb_{ex}$ (CRS) in an approximate form, where the M90 level is individuated, and which should correspond to about 74 yr. M90 is the depth at which the $^{210}Pb_{ex}$ inventory corresponds to 90 % of its total value. The use of other more complex models would be possible (e.g. Sorgente et al. 1999). However, results obtained using our simple assumptions were in close agreement with meteorological and river flux information (see Section 4.2) and therefore acceptable.

Since we could not correct the accumulation rates for physical mixing and bioturbation, all values should be considered as upper limits.

4. RESULTS

4.1. Meteorological and hydrological records

AT and ABP Qmean records (1922–2000) were 210.3 and 219.3 m^3 s^{-1}, respectively, with average yearly cycles shown in Fig. 2. The peak discharge is in June, whereas a second maximum occurs in October and November. The winter season is characterized by relatively low values.

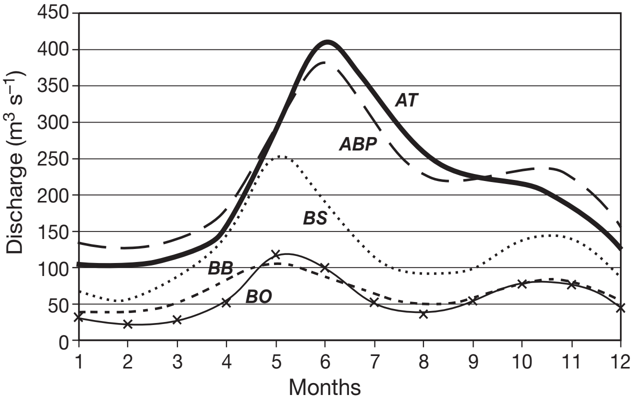

Fig. 2. Mean yearly cycle for the Adige and Brenta rivers (hydrological stations averaged over the investigated period). AT: Adige Trento, ABP: Adige Boara Pisani; BS: Brenta Sarson (before 1940), BB: Brenta Barziza (after 1947), BO: Brenta Ospedaletto (1935–1954)

The results of the application of the Mann-Kendall test to seasonal and annual TP, WD, PI, Qmax and Qmean are summarized in Table 1. Regional TP does not show any significant trend in the 1922–2000 period, neither on seasonal nor annual scales (Fig. 3). Annual WD and PI show a decrease (0.6 d $decade^{-1}$) and an increase (0.07 mm d^{-1} $decade^{-1}$), respectively. The WD decrease is mostly due to the 1930–1950 and 1960–1990 time intervals (Fig. 3).

Qmean at ABP is characterized by a decrease (Fig. 4) throughout the whole period, with present values 30% lower than the former, compared to a 14% decrease at AT. This means yearly reductions in average river flow of 11 and 7 m^3 s^{-1} $decade^{-1}$ at ABP and AT, respectively (Table 1). Seasonal records at ABP (Fig. 4) show that a drop of ~50% in summer is mainly responsible for the yearly trend.

Since the ABP record is the most complete and continuous, and also includes data about transport of suspended solids, in the following we will discuss seasonal trends and solid discharges using this dataset.

Though limited, the Qt data set at ABP provides useful information (although it is not possible to estimate its trend, nor to give statistical significance since the series is incomplete, lacking a rather long period of data). A qualitative analysis of the data obtained by calculating the averages over the 2 periods shows that the yearly mean values are 37 and 26.2 kg s^{-1}, respectively, with a net decrease of 29%. Analysis of the seasonal records (Fig. 5) shows a general decrease in summer (–43%), autumn (–30%) and spring (–11%) mean loads, corresponding to a rather significant loss of total solid fluxes (–100, –38 and –11 kg s^{-1}, respectively), compared to the increase of winter loads (+18 kg s^{-1}). Interannual variability of solid discharge differs between the 2 periods, with rather high oscillations in the former, particularly in spring, compared to more uniform turbidity levels after the 1950s. Avanzi (1976) observed for the same period a smoothing of the yearly Qmean since the 1950s with an attenuation of the summer levels and a slight increase in winter, suggesting that the presence of dams enhances seasonal

Table 1. Mann-Kendall test and least square linear fitting to the 7 datasets. **Bold**: $p < 0.01$; *italics*: $p < 0.05$; other numbers: $p < 0.1$; + or –: sign of the slope ($p > 0.1$); dots: null trend values. WD: number of wet days; PI: mean amount of precipitation per wet day (precipitation intensity); TP: total precipitation; Qmax: maximum river discharge; Qmean: mean river discharge; ABP: Adige Boara Pisani; AT: Adige Trento

Trend per decade	Winter	Spring	Summer	Autumn	Year
WD	–	–	+	–	–0.6 ± 0.5
PI	+	…	…	+	0.07 ± 0.04
TP	–	–	+	…	…
Q_{max}(ABP)	–	*–21 ± 8*	**–34 ± 8**	*–28 ± 14*	**–21 ± 6**
Q_{max}(AT)	*2 ± 2*	–	*–20 ± 10*	–	–15 ± 6
Q_{mean}(ABP)	…	–7 ± 4	**–27 ± 5**	*–9 ± 5*	**–11 ± 3**
Q_{mean}(AT)	3 ± 1	–	**–19 ± 5**	–	–7 ± 3

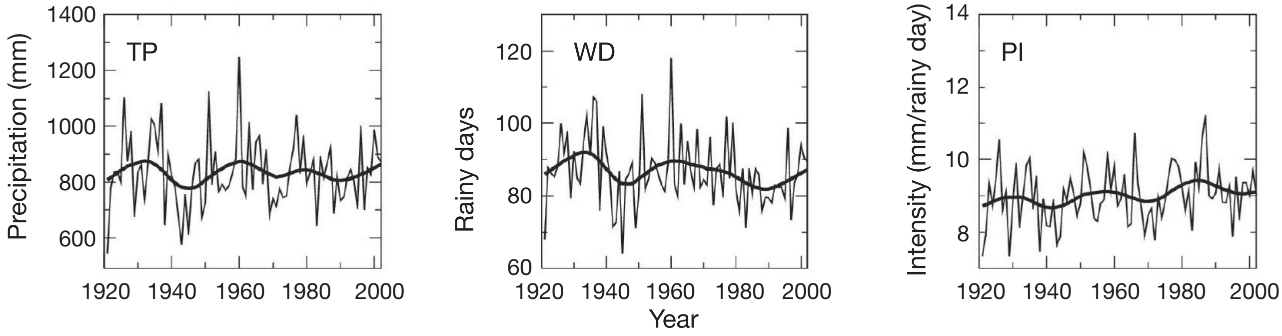

Fig. 3. Yearly series of total precipitation (TP), number of wet days (WD), and mean amount of precipitation per wet day (precipitation intensity, PI) in the Adige River basin. Thick black lines: 5 yr σ Gaussian filtered series

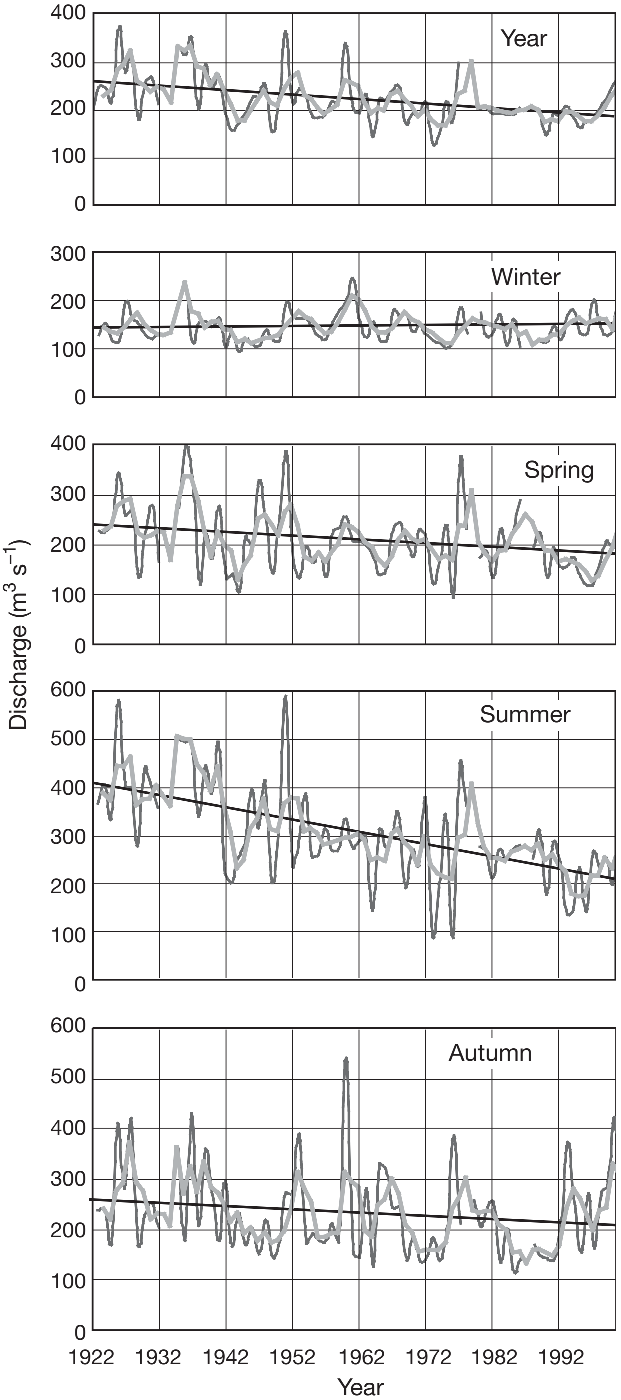

Fig. 4. Annual and seasonal mean discharge (Qmean, m^3 s^{-1}) for the Adige River, ABP station, 1922–2000. Black: regression; light grey: 3 yr running mean; dark grey: annual data

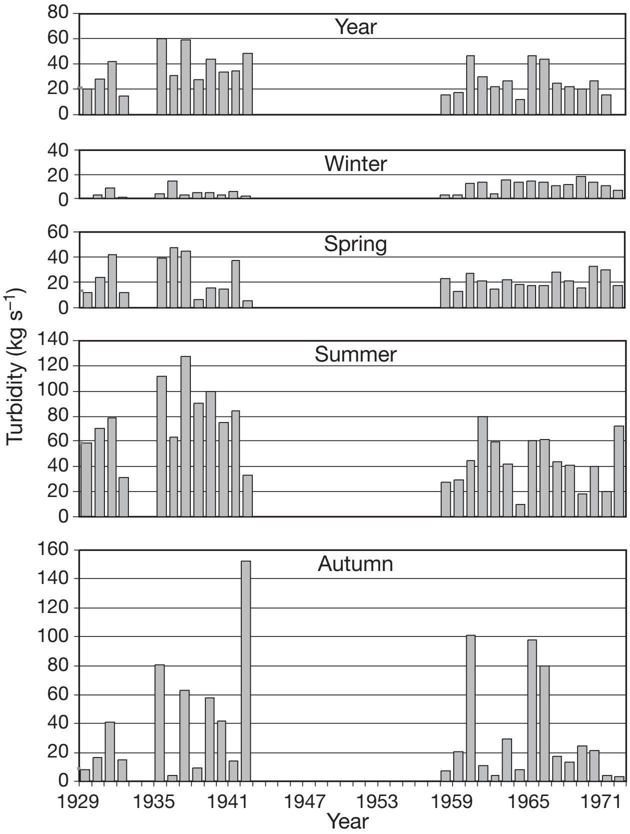

Fig. 5. Annual and seasonal mean specific turbidity (Qt, kg s^{-1}) at ABP, 1929–1942 and 1958–1972

uniformity. The relationship between solid and liquid discharges in the 2 periods (Fig. 6) reveals only a slight change in the monthly values, even if the co-variance drops from 83 to 54 %, whereas the seasonal change of pattern is very clear: winter values (Fig. 6b) show a general increase of solid discharges in the 1958–1972 period, without any correlation to liquid discharges; in the other seasons (Fig. 6c–e) a general smoothing of the values is recorded, particularly for spring, and a pronounced decrease in summer values.

4.2. Marine sedimentary record

The material accumulated at the sampling sites on the Adriatic shelf is generally fine, with silt always being more abundant than clay. The sand content is generally low (1–4 %) except for some sand-rich layers (up to 40 %) at the base of core ATA89-24. These features suggest that the sedimentary environment is usually subject to moderate hydrodynamics without substantial sedimentary variations, especially over the last 80–90 yr.

The 4 cores show rather uniform distributions of sedimentological features. However, colour changes are visible in the uppermost parts of cores ATA89-24, NAR88-6 and AAS86-47 at 13, 28, and 13 cm depth, respectively, whereas this feature is not clearly visible for core AAS86-57, because it appears disturbed above 18 cm. The depths of color discontinuities approximately coincide with those related to the main features of the porosity depth distributions, shown in Fig. 7 together with the profiles of magnetic susceptibility. Both parameters show a correlation between cores NAR88-6 and AAS86-47 on one hand, and cores ATA89-24 and AAS86-57 on the other. This reflects locally different sedimentary regimes on a short spatial scale, as a result of very shallow water depth, hydrodynamic features and presence of important river discharges. It is also interesting to observe that the depth profiles of porosity show a series of discontinuities, in the form of positive and negative peaks (Fig. 7a).

Fig. 8 shows the activity-depth profiles of $^{210}Pb_{ex}$ and ^{137}Cs. The most important features of $^{210}Pb_{ex}$ distributions (Fig. 8a) are the deviations from the ideal exponential decrease, which, in some cases, are related to a discontinuity in the porosity profile. The most irregular $^{210}Pb_{ex}$ patterns are shown by cores AAS86-47 and AAS86-57. The peaks in the topmost layer (~8 cm thick) are possibly due to recent episodes of pulse accumulation. ^{137}Cs profiles (Fig. 8b) are not very helpful because the peak caused by the release of radioactive materials from the Chernobyl nuclear power station is very close to the surface, due to the short time between the contaminating event (1986) and core collection. Furthermore, since ^{137}Cs can migrate within the sediment, other time markers, such as the base of the profile (i.e. the onset of nuclear weapon testing in 1954) and the downcore peak corresponding to the maximum number of atmospheric nuclear tests in 1963, are not very reliable.

The results of sediment accumulation rate calculations are listed in Table 3, which reports the values obtained by means of 3 different models. In order to assess the ages of sedimentary levels, we used CF-CS rates for all cores. This choice allowed us to obtain very comparable chronologies for the main sediment features at all core sites.

5. DISCUSSION

The correlation between meteorological and hydrological parameters indicates that at both AT and ABP the discharge is mainly regulated by TP and WD, with slightly higher values for the former (Table 2). At both locations, correlation between TP and Qmean–Qmax is highest in autumn and lowest in summer. Correlation coefficients for the monthly data (Fig. 9) exhibited a pronounced drop in June, particularly for Qmean, whereas the decrease of correlation is similar and less important in the other summer months. This suggests the lack of correlation between precipitation and water discharge limited to only one summer month is related

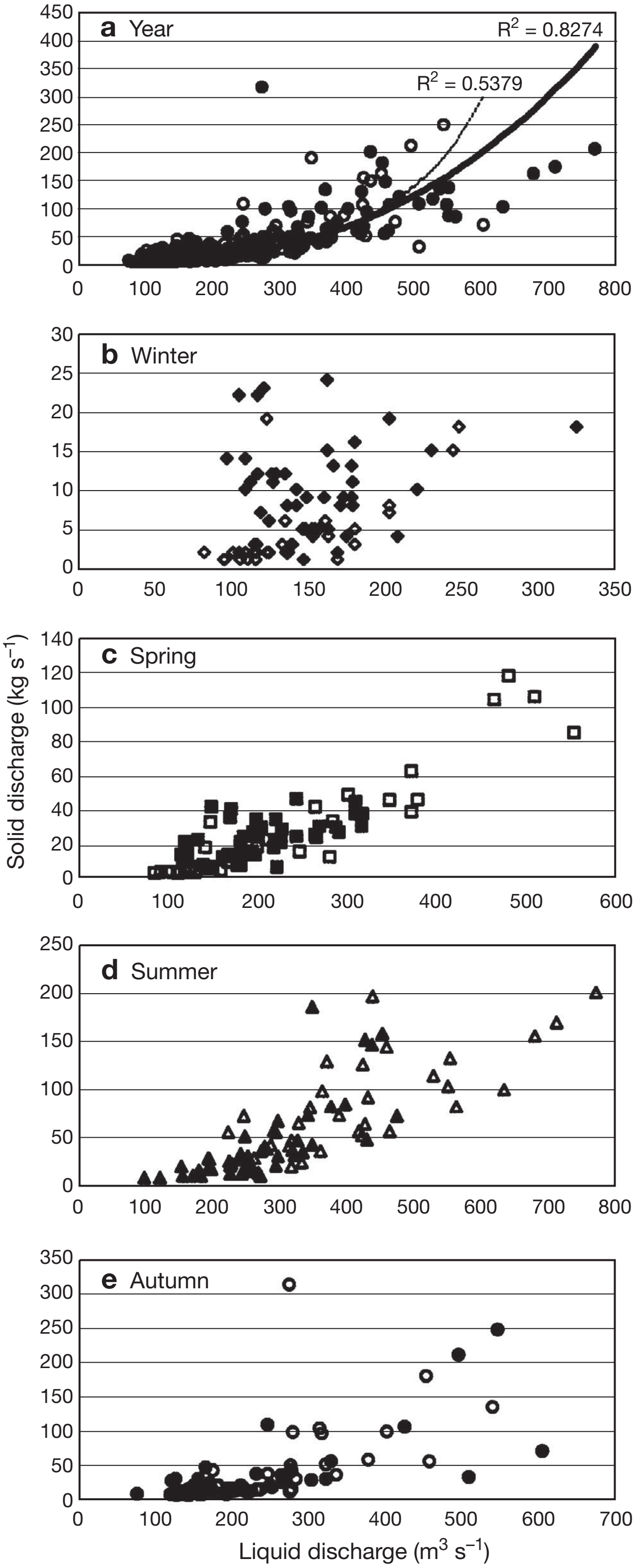

Fig. 6. (a) Yearly and (b–e) seasonal relationship between liquid and solid discharges during 1929–1942 (solid symbol) and 1958–1972 (open symbol), and related regression lines (continuous line for the first period and dotted line for the second) with co-variance factor. Single points: mean monthly values

Table 2. Correlation coefficients between precipitation and discharge of the Adige River. **Bold**: $p < 0.05$. See Table 1 for abbreviations

Correlation	Winter Qmean	Winter Qmax	Spring Qmean	Spring Qmax	Summer Qmean	Summer Qmax	Autumn Qmean	Autumn Qmax	Year Qmean	Year Qmax
TRENTO										
TP	0.23	0.41	0.64	0.63	0.17	0.25	**0.87**	**0.85**	**0.77**	**0.75**
WD	0.17	0.33	0.59	0.51	0.14	0.14	**0.76**	**0.72**	**0.71**	0.59
PI	0.05	0.17	0.46	0.51	0.13	0.28	0.60	0.62	0.45	0.46
BOARA PISANI										
TP	0.32	0.57	0.65	0.69	0.14	0.27	**0.85**	**0.84**	0.68	**0.74**
WD	0.34	0.54	0.62	0.57	0.10	0.14	**0.78**	**0.72**	0.67	0.64
PI	0.06	0.31	0.44	0.51	0.14	0.30	0.56	0.59	0.37	0.41

Table 3. Sediment accumulation rates (cm yr^{-1}) at selected sites. Values obtained using the CF-CS, CIC and CRS (as M90) models. See Section 3.5 for abbreviations and definitions

Core	ATA89-24	NAR88-6	AAS86-47	AAS86-57
CF-CS	0.59	0.65	0.44	0.51
CIC upper	0.50	0.51	0.27	0.32
CIC lower	0.63	0.69	0.44	0.50
M90	0.55	0.63	0.38	0.51

to the delayed effect of melting snow on river discharge rather than to withdrawal for irrigation purposes, i.e. a natural, rather than an anthropogenic, cause. Winter months exhibit a second maximum in the correlation between TP and Qmax at ABP. Moreover, at AT (Fig. 9a) during the January–May period, Qmean and Qmax are both less correlated with TP ($r = 0.15$ to 0.45, with a minimum correlation in February) than at ABP ($r = 0.35$ to 0.65) (Fig. 9b). The different winter/early spring pluviometric regimes of the alpine and lowland sectors of the basin (characterised by maximum precipitation in summer, and in spring and autumn, respectively) can be interpreted as a result of the direct effect of precipitation events on the river flow at different locations; while the mountain basin is usually affected by snow during this period, rainfall is the main component of the precipitation in the lowland. Therefore, we can expect a closer correlation between precipitation and river discharge at ABP, because much of the ABP precipitation is solid (i.e. snow, hail etc.) with no direct effect on the river discharge. On the other hand, the very high correlation coefficient found for the autumn season at both sta-

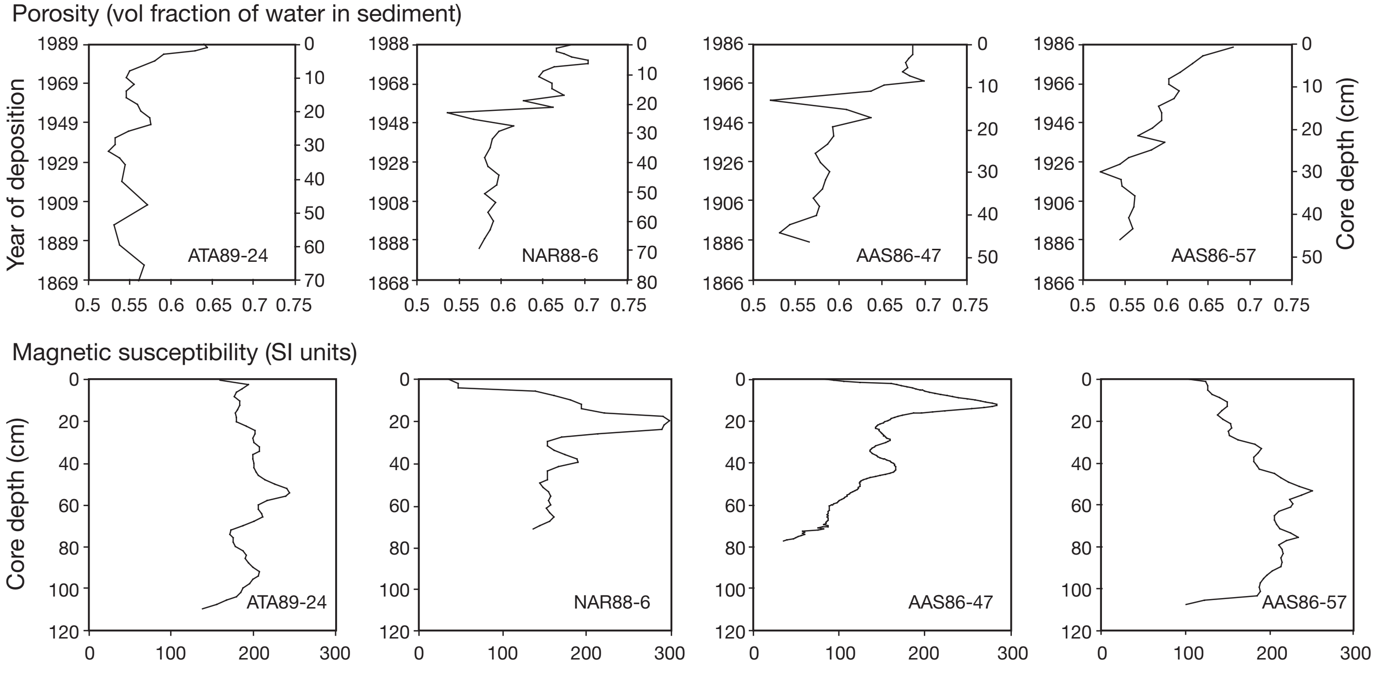

Fig. 7. Porosity and magnetic susceptibility profiles for the 4 cores ATA89-24, NAR88-6, and AAS86-47 and -57 (North Adriatic shelf)

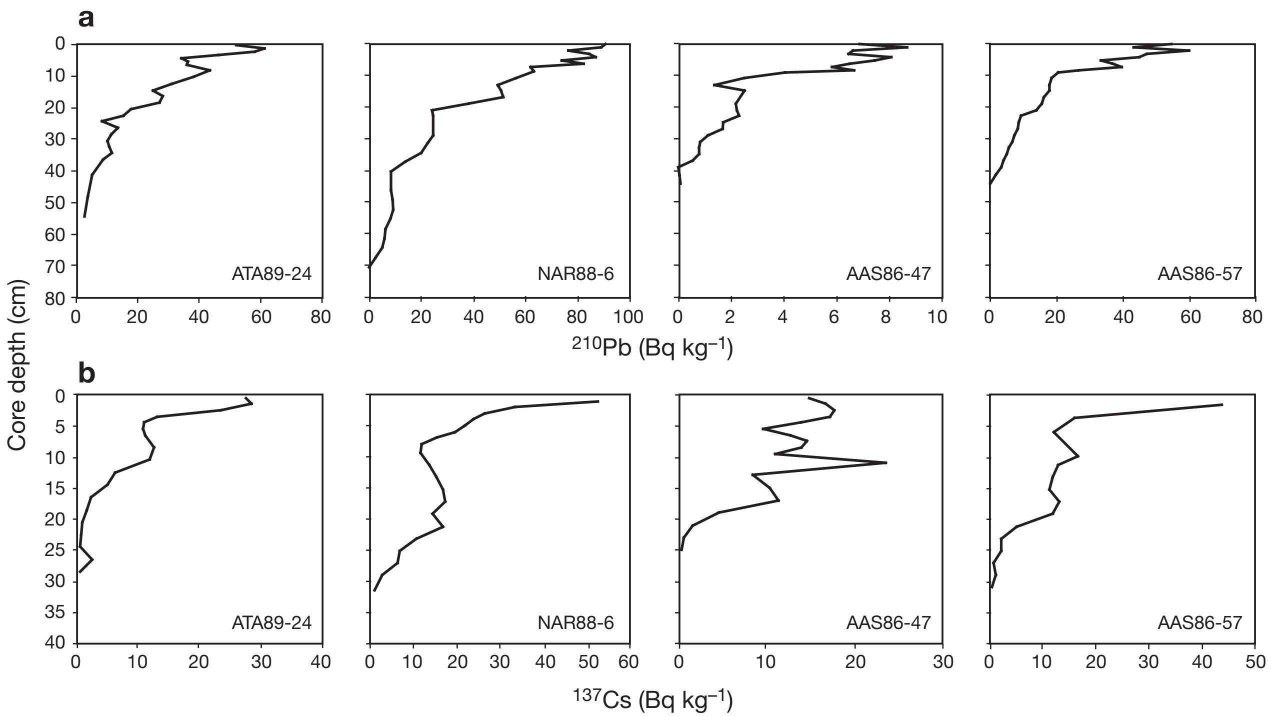

Fig. 8. Activity-depth profiles of (a) ^{210}Pb and (b) ^{137}Cs in sediment cores ATA89-24, NAR88-6, and AAS86-47 and -57

tions seems to be the result of the direct impact of precipitation, in both cases represented mostly by rain, on river discharges (Fig. 9a).

Annual Qmean and Qmax at AT and ABP (Fig. 10) confirm the agreement between TP and runoff. Moreover, they account for much higher discharges at ABP than at AT, as a result of the relative extension of their drainage basins (12 000 and 9800 km^2, respectively). Independent parameters such as the meteoric afflux, defined as the total volume of annual precipitation over the drainage area upstream from a hydrological station, consistently show higher values at ABP than at AT over the same period, whereas after the mid-1950s the 2 curves almost overlap, mainly as a consequence of the drop in ABP values. Unfortunately, we cannot precisely detect the time of this change, due to the lack of data for AT over this time interval. After the beginning of the 1970s, an inversion of the 'natural' behaviour can be observed, with AT values higher than ABP ones. Avanzi (1976) found that flood seasonality also shows an inversion across the 1950s: ordinary floods (800 to 900 m^3 s^{-1}) become more frequent in winter than in summer, while extraordinary events (>900 m^3 s^{-1}) move to the summer season.

Fig. 5 shows a slight increase in solid discharge during the winter over the second period (1958–1972), whereas the other seasons display a decrease in total solid transport, in agreement with the Qmean pattern (Fig. 4). Co-variance decreases in the plot of bulk monthly data (Fig. 6) suggesting the presence of other non-natural factors influencing the solid/liquid discharge relationship during the second period. In this case, the winter is characterised by a general increase in solid transport not always related to a corresponding

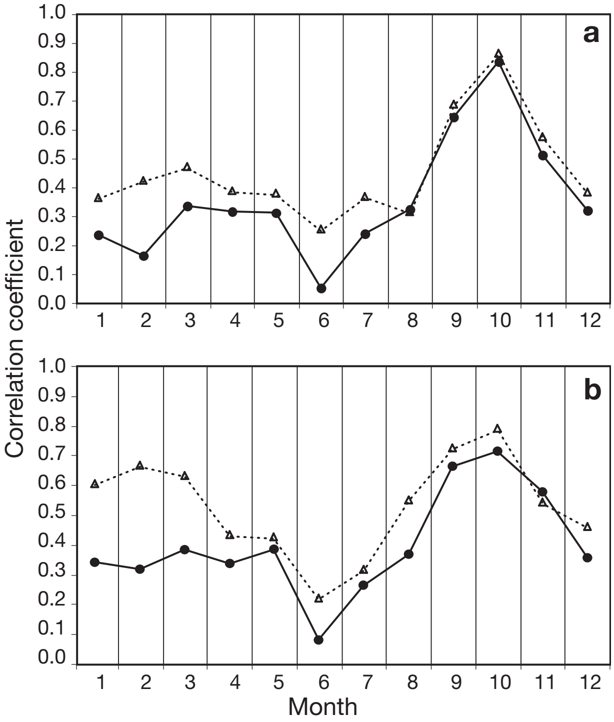

Fig. 9. Monthly correlation coefficients between mean monthly TP and Qmean (●) and Qmax (△) at (a) AT and (b) ABP

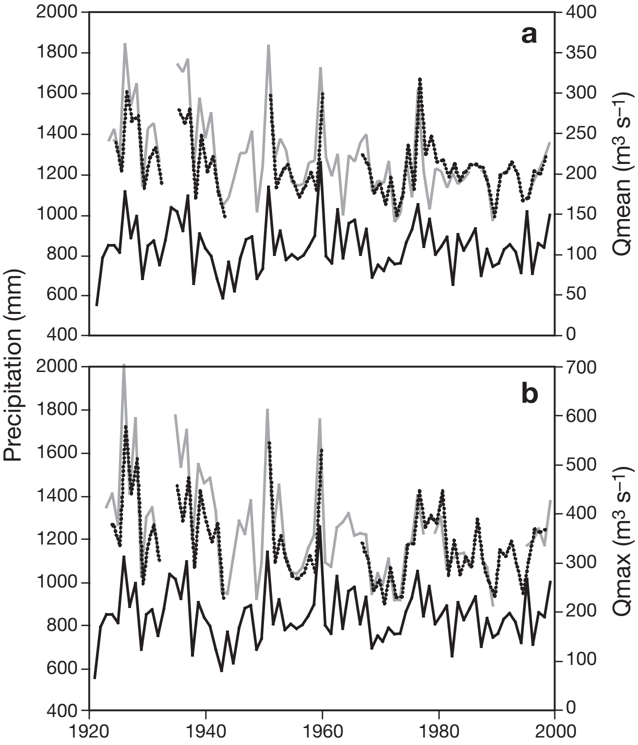

Fig. 10. Annual total precipitation (black line), and river discharges at AT (dotted line) and ABP (grey line) for (a) Qmean and (b) Qmax

increase in liquid discharges, whereas a more or less pronounced decrease in both solid and liquid discharges takes place in the other seasons. Moreover, the general smoothing of the interannual variability toward lower values shows the close connection between liquid discharge and transport capacity of suspended sediment across the river system, and the sensitivity of both parameters to hydrological changes, whether natural or not, occurring in the drainage basin.

The major discontinuity between the end of the 1940s and the beginning of the 1950s is also demonstrated by the application of the Craddock (1979) test, which is used to identify possible inhomogeneities due to non-climate changes, between TP and Qmean and Qmax. The curves (Fig. 11) show a downward shift of the ratios between total precipitation and mean flow in the 1922–2000 period. The inhomogeneity is present at both ABP and AT, but is stronger at ABP. This makes us confident that this feature is not due to changes of either measurement procedures or location.

The inhomogeneities seem to be closely connected to the enhanced human activity in this area since the end of World War II when, in order to support the intensive agricultural effort on the Veneto plain, farmers started to exploit river water for irrigation purposes. Seasonal discharge records (Figs. 4 & 6) confirm this hypothesis, since the main decrease takes place during the summer, which today shows values that are half of those in the 1920s. Moreover, the building, reinforcement and elevation of the levees and, most of all, the presence of dams and reservoirs, had a profound influence on the strong decrease in liquid discharge. The contemporary use of water and sediment for the 'civil reconstruction phase' and the presence of other human-made structures, such as dams in the mountain sector for electric power generation, also had a significant influence on the decrease in solid discharges, as discussed by Dal Cin (1983). The observed decrease involves the solid transport of both fine suspended load and coarse bed load sediments, which decreased markedly (–23%) from 1922–1950 to 1958–1975 (Fig. 12). This seems to account for the removal of sandy sediments from the river bed since the 1950s.

A major discontinuity in sediment features on the Adriatic shelf around the late 1940s and early 1950s is especially visible in core lithology and in the depth distribution of both porosity and $^{210}\mathrm{Pb}_{\mathrm{ex}}$. Sediment accretion rates have decreased in recent times, as shown by the CIC accumulation rates. The accumulation pattern is characterized by a series of single, probably more intense, depositional events. This is particularly true for cores AAS86-47, AAS86-57 and NAR88-6, which present a series of peaks close to the surface.

In conclusion, the shelf sediments seem to reflect the main hydrological changes which have occurred in the river basin as a result of both climate trends, such as

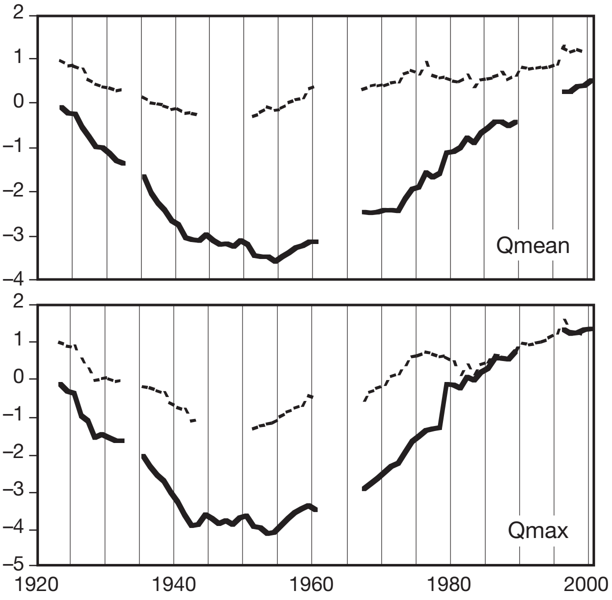

Fig. 11. Results of the Craddock test applied to Qmean and Qmax at AT (dashed line) and ABP (black line) assuming TP as reference series

the increase in PI over the recent past, and anthropogenic forcing, such as the withdrawal of water and sediments. The response of fine-sediment marine records to these causal factors is quite synchronous, even when accounting for all the dating problems, suggesting that the shelf environment responds quickly to climate and natural hydrological changes as well as to inland use of river water and sediments. Coarse bed load sediment, on the other hand, seems to respond with a delay of at least 10 yr in the marine records. Bed load has decreased in the river basin since the 1950s, and Bondesan & Simeoni (1983) reported a net retreat of the submerged beaches beside the river mouths starting from the beginning of the 1960s. In addition to post-war human intervention in the drainage basin, intense quarry activity also made a significant contribution to the profound changes observed in the hydrological regime. River bed erosion, currently observed in the Adige and Brenta rivers, is partially compensating the decrease of solid discharge to the sea that would otherwise be much more important (Dal Cin 1983). On the other hand, river bed erosion will induce a destabilisation of the hydrographic curve, enhancing erosional phenomena and hydrogeological failure along the drainage system.

6. CONCLUSIONS

The main results of this study are:

(1) The rainfall pattern shows only minor variations over the period 1922–2000, with a slight decrease in total precipitation (statistically non-significant) coupled by a decrease in WD and an increase in PI. This pattern is common throughout Italy (Brunetti et al. 2004).

(2) Correlation analysis between meteorological variables and river hydrology shows that the most representative parameters affecting river flows are total precipitation and WD, with a slightly higher correlation for the former.

(3) River liquid discharge decreases throughout the whole period studied, particularly during the summer, with a major discontinuity in the 1950s for both solid and liquid discharges.

(4) A decrease in sediment accumulation rates, starting around the late 1940s/early 1950s, can be recognized in the marine sedimentary record.

(5) These changes seem to be mostly due to anthropogenic activities rather than to climate change. The progressive withdrawal of river water for irrigation (starting from the 1950s) played a major role, immediately affecting the supply of water and suspended load to the shelf. On the other hand, the decrease in supply of coarser sediment to the coastal areas since the 1960s seems to be mostly the result of river damming and excavation of sands from the river bed. The removal of sand, particularly important for the evolution of the coastal areas, was recorded at sea with a 10–15 yr delay.

(6) A further decrease in liquid discharge, starting in the 1970s, has been recorded on the shelf. This trend is characterised by the intermittent accumulation of fine sediments, which probably reflects major floods.

(7) The changes in the precipitation pattern, with more intense events distributed over fewer days, could give rise to difficult-to-predict responses of the hydrological regime. This is especially likely with hydrological changes resulting from continued human activity, particularly for factors affecting liquid and solid river discharge, such as different temporal distribution of the flooding seasons and/or changes in the sediment transport and distribution (suspended vs. bed load) within the river and in the coastal areas.

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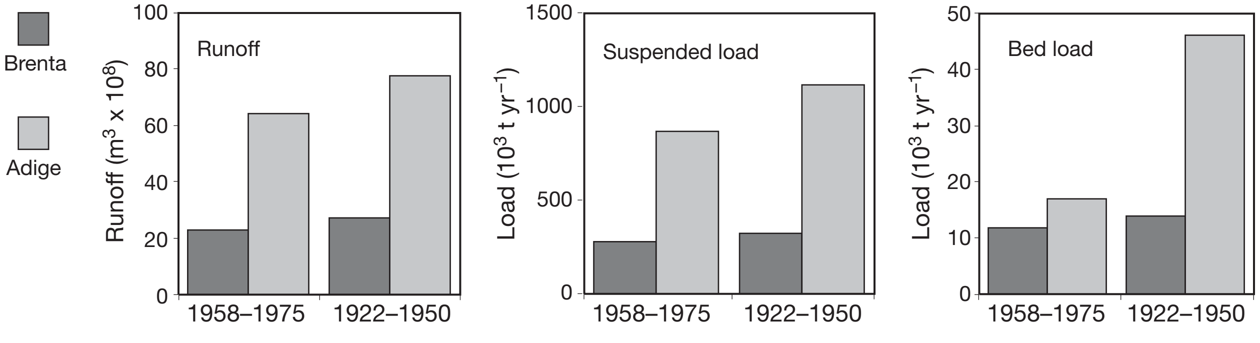

Fig. 12. Comparison of total annual runoff, suspended and bed load during 1922–1950 and 1958–1975 for the Adige and Brenta rivers

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